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Reexamination of Color Vision Standards, Part II. A Computational Method to Assess the Effect of Color Deficiencies in Using ATC Displays

Jing Xing
David J. Schroeder
Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

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16. Abstract

The previous study showed that many colors were used in air traffic control displays. We also found that colors were used mainly for three purposes: capturing controllers' immediate attention, identifying targets, and segmenting information. This report is a continuing effort to reexamine the FAA's color vision standards, focused on understanding how individuals with color vision deficiencies use color-coded information. We first reviewed and synthesized the literature about the effectiveness of color relative to achromatic visual cues. Next, we developed several algorithms to assess the effects of color for individuals with color vision deficiencies. Using a computational algorithm that simulates how color deficient individuals perceive color, we were able to calculate the effectiveness of color in task performance. By considering together the effectiveness of redundant visual cues and the perception of those with color vision deficiencies, we provide a method to assess the potential effects of color deficiencies in using color displays.

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REEXAMINATION OF COLOR VISION STANDARDS, PART II. A COMPUTATIONAL METHOD TO ASSESS THE EFFECT OF COLOR DEFICIENCIES IN USING ATC DISPLAYS

INTRODUCTION

People with normal color vision have three types of cone receptors in their retinas to perceive color. Each type of cone receptors contains a photopigment that responds to a restricted range of the light spectrum corresponding to red, green, or blue. *Color deficient individual* (CD) is a term denoted to a person who has abnormal or incomplete cone receptors. Compared to color-normal individuals (CN), CDs perceive a reduced range of color because of the absence of some types of cones. Roughly 8-10% of all males are CDs, while very few females are CDs. There are three types of CDs. 1) Anomalous trichromats have all three types of cones but one cone type is rare. Such individuals can see all color categories but have difficulty in discriminating color that a normal vision person can easily distinguish. 2) Dichromats have only two primary cones; one type is missing. Dichromats are further classified into three types: protanope, deuteranope, and tritanope. Protanopes and deuteranopes constitute the majority of CD populations. They have red-green color deficiencies and see only yellow and blue. The tritanope is analogously blue-yellow color deficient. 3) Monochromats have no cones and therefore no color vision at all. They are very rare, about one in ten million people.

Given that color displays are being widely used in many professions including air traffic control (ATC), it is important to understand how CDs perceive colors. Brettel, Vienot, and Mollon proposed an algorithm to simulate for normal observers the appearance of a color image for individuals with dichromatic types of color deficiencies (Brettel, Vienot, & Mollon, 1997; Vienot, Brettel, & Mollon, 1999). Inspired by Brettel's work, Dougherty developed a computer program, called *Vischeck*, to simulate the entire color process of human vision (see www.vischeck.com for reference). The *Vischeck* model can be divided into three stages. The first stage includes the physical properties of display devices, ambient lighting, and physiological factors. The second stage describes the transformation of an optical image on the retina into a neural representation of that image. This stage used Brettel's algorithm to model the effects of dichromats. The final stage is a model of human cortical vision. This stage includes mechanisms in which color, spatial patterns, and motion are combined and processed in the visual cortex to form the observer's perception of the image. Figure 1 shows a simulation sample obtained from the *Vischeck* program. The figure presents the images seen by deuertanopes and protanopes after transformation of each pixel of the original image. Figure 1 indicates that most colors appear darker and less saturated for CDs. For example, red and green appear dark yellowish. Overall, CDs generally

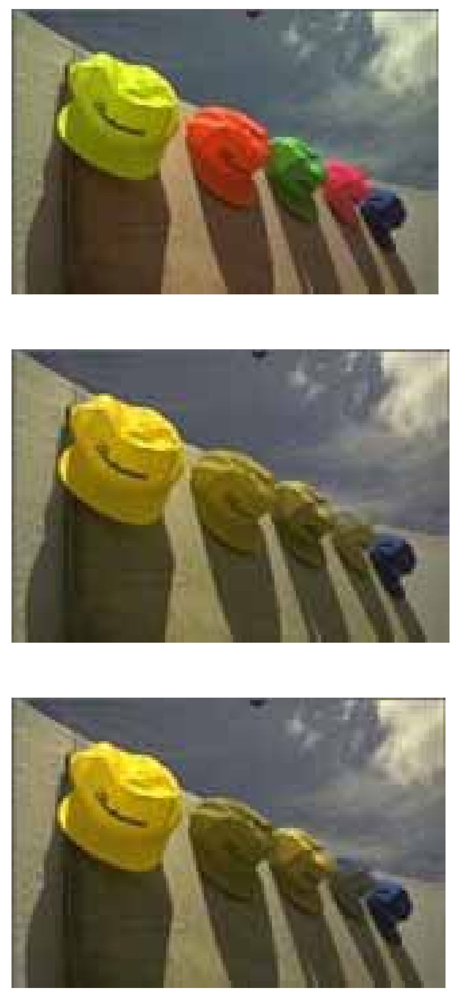

Figure 1: An example of color-deficit simulation produced by the *Visckeck* program. The top image shows some colorful hats seen by color-normal observers; the middle is the image as seen by a person with deuteranopia; the bottom is the image as seen by a person with protanopia.

can see colors to a certain extent, but they have trouble distinguishing between some shades of red and green or blue and yellow. They also cannot differentiate some colors that are perceptually close to each other.

Our previous study (Xing & Schroeder, 2005) demonstrated that the color vision standards currently used by the FAA have allowed certain types of CDs to pass the practical color vision screening tests for air traffic control specialists. However, in the past five years there has been an increased use of color in displays being introduced in ATC facilities. Controllers with color vision deficiencies may experience difficulties in using color-coded information appropriately, because color deficiency was not a consideration at the ATC display design.

Simulation programs such as *Vischeck* provide a means to explore how the ATC displays would appear to CDs. However, not only do we need to know how colors appear to CDs, but we also need to determine how reduced color perception affects task performance. Our previous study has shown that colors on ATC displays are used for three purposes: 1) to capture attention; salient colors are often chosen to encode information that needs to be attended to immediately, such as an alert or emergency; 2) to identify categories of information so that searching for specific information in a complex image can be done more effectively; in this case, each color is associated with a distinctive meaning; 3) to segment complex images in a display into distinctive groups so that information belonging to the same category can be organized together. In this application, color does not have inherent meanings. Therefore, we use three terms to refer to color-related tasks throughout this report: *attention, identification,* and *segmentation.* We synthesized the literature for studies on the use of color in these types of tasks. Using the experimental data in the literature as criteria, we were able to assess the potential effects of color use for CDs.

Our previous observations of ATC displays revealed that color was often used along with achromatic redundant cues (ibid). Presumably, redundant cues would allow CDs to perform the tasks. However, redundant cues may not be as effective as colors in supporting task performance. Therefore, when assessing the effects of color vision deficiencies on task performance, we have to consider the effectiveness of redundant cues, together with the reduced color perception of CDs. In this report, we analyzed the effects of achromatic cues relative to colors, and we developed a set of computational algorithms to compare the effectiveness of colors for CDs versus CNs. Furthermore, we applied the algorithms to the general use of color in ATC displays. The results are presented in several look-up tables that can easily be used to assess the effects of color vision deficiencies for a given display.

This report has two major parts: 1) rationales for the effectiveness of color based on research data in the literature; and 2) algorithms we developed to assess the effects of colors for CDs. We also discuss the potential applications and limitations of the algorithms in evaluating ATC color displays with respect to CDs.

RESULTS

Rationale for the usefulness of color

This section synthesizes the research literature to provide a rationale for the effectiveness of color in displays. Such a rationale is the basis for the algorithms described in the following section. Given that colors in ATC displays are used mainly for three types of tasks: *Attention, Identification,* and *Segmentation,* this section is focused on visual studies in which subjects performed tasks involving those activities. In addition, we also reviewed studies of text readability associated with colors. Reading text from displays is an important part of ATC tasks. Even though the use of colors in a display is not designed to influence text readability, applying color to text nevertheless affects readability.

Color can be specified by two factors: luminance and chromaticity (hue). Our literature review was intended to elucidate the relationship between the effects of color use and color specifications. In particular, we sought to determine the threshold point for color specifications, below which color is no longer effective for a given purpose, and the saturation point, beyond which the effectiveness of color does not increase further. Since these critical points might vary with experimental conditions, we relied more on studies conducted using complex images on large displays (mimicking the situations of ATC).

Introduction to color systems

A color system refers to the mathematical description of colors. A full description of color includes two factors: chromaticity (hue) and luminance (brightness). There are many kinds of color systems developed for different purposes. Here, we briefly introduced several systems used in this report.

As mentioned earlier, human retinas have three types of cones that are sensitive to colors. Each type is sensitive to a special region of the light spectrum (Long, Medium, and Short). Thus, a cone is referred to as L-, M-, or S-cone, each for its sensitive region of the light spectrum. An L-cone has its peak sensitivity to red; an M-cone is most sensitive to green, and an S-cone spreads over the blue region of the light spectrum. The excitation of each type is denoted with L, M, and S. Therefore, a color can be specified with these three values of cone excitation.

The proportion of stimulated L-, M-, and S-cones determines the chromaticity of a color, while the luminance of a color is the sum of excitation of all cones, i.e., (L+M+S). This system is best suitable to describe color deficiencies because certain types of cones are absent in CDs (Wandell, 1995).

While the LMS systems describe the activity in the retinas induced by a color, its variables cannot be measured directly. On the other hand, The International Committee of Illumination (CIE) defined color chromaticity coordinates to describe color perception. In this definition, a color can be specified by three parameters: *L, x,* and *y,* where *L* is the luminance of a color and *x* and *y* determine the chromaticity. A colorimeter can measure the *Lxy* values of a surface. Because of its ease of measurement and independence from observers, CIE chromaticity is the most widely used color system. However, one of the greatest disadvantages of the CIE chromaticity systems is that visually they are not equally spaced. Thus, distortions occur in attempting to relate perceived colors to locations of the CIE chromaticity diagram. Based on the *Lxy* systems, the CIE adopted the *Lu′v′* systems that were more nearly uniformly spaced with respect to color perception. Therefore, the chromaticity difference between two colors can be computed as $((\Delta u')^2 + (\Delta v')^2)^{1/2}$. The values of u' and v' can be computed from *x* and *y* through two non-linear equations.

A computer display generates a color through three phosphor channels: red, green, and blue. The amount of phosphors emitted from each channel is specified with the digital value of the channel: *r, g*, or *b*, each for red, green, or blue phosphors. Computer programmers use these numbers to specify a color on displays. For example, *rgb* values of (255, 0, 0) are for red and (255, 255, 0) are for yellow. The relationship between the *rgb* and *Lxy* systems can be easily specified with a nonlinear transformation and a linear matrix transformation. The process of determining the transformations is called *color calibration*.

Besides the above color systems, there are many other mathematic descriptions of color. The good news is that these color systems can be transformed from one to another by a set of mathematical equations. In this report, we used the CIE uniform chromaticity systems (*Lu′v′*) to describe color differences. While the results in the literature were expressed in different systems, we converted those data into *Lu′v′* specifications. Since the transformation from *rgb* values to other color systems requires calibration of the monitor, we adopted the default monitor calibration parameters used in the *Vischeck* program, as shown in the Appendix A.

Attention

Critical information presented on ATC displays needs to be detected immediately without serial searching through a display. Therefore, the target should become obvious immediately to capture an observer's attention. This phenomenon is called "pop-out." Treisman and Gelade (1980) found that a number of visual attributes could induce pop-out and by doing so allow information to be extracted in parallel across a large visual field. By parallel, we mean that the amount of visual stimuli on a display has little effect on the time and accuracy of target detection.

Pop-out of color-coded information is extremely efficient and desirable at display design (Treisman & Gelade, 1980). Colors help when targets need to be detected in large displays. By popping out, targets located in the peripheral visual field can be brought quickly to the fovea for detailed inspection. Christ (1975) also confirmed that introducing colors on large displays helps detection because information could be processed in parallel.

Many studies have been devoted to the effectiveness of visual attributes in drawing attention. Christ (1975) compared the data in the literature and concluded that color was the most effective cue to draw attention in complex scenes, followed by luminance and shape. On the other hand, Banks and Weimer (1992) examined subjective evaluations using visual features to highlight alert messages. Their results indicated that flashing was ranked as the top choice, followed by brightness (luminance), color, and then attributes such as size and shape. While flashing is most effective in drawing attention, its use should be limited because it produces tunnel vision, in which the observer focuses on the target and ignores other information in the visual field.

A number of studies have demonstrated that visual conspicuity draws attention instantly. For static visual stimuli, the conspicuity of a target is mainly determined by two factors: color and luminance differences between the target and other stimuli in the visual field (referred to as distractors). Johnson, Liao, and Granada (2002) reported that visual conspicuity of aircraft symbols increased linearly with the target luminance. Their results suggested that there was no saturation point for the effectiveness of luminance in drawing attention. Wyszecki and Fielder (1971a) reported that the threshold luminance difference for *Attention* is about 75 times the threshold at which the target and distractors could be discriminated. Nagy and Sanchez (1992) found that the threshold luminance difference varied with the size of displays and stimuli. They demonstrated that, if the luminance difference between the target and distractors was larger than ~10 cd/cm^2 on a small display field and ~20 cd/ cm^2 for small stimuli (~1.5cm, 0.5 degree) on

a large display field, observers could detect the target instantly without searching among distractors. They also showed that there was no advantage for combining a luminance difference with a chromaticity difference when the target was brighter than the distractors. On the other hand, a target dimmer than distractors could hardly capture attention. In that situation, an additional chromaticity difference might be helpful.

Much effort has been made to determine the threshold chromaticity difference between a target and distractors in attention capture. Carter and Carter (1981) concluded that the difference should be at least 7~13 times the color-discrimination threshold (the one determined by Wyszecki & Fielder, 1971a,b). Nagy and his colleagues performed a series of studies to determine the threshold difference by varying display size, stimulus size, and stimulus location in the visual field (Nagy & Sanchez, 1990; Nagy, Sanchez, & Hughes, 1990). The situation that was most similar to ATC displays was the combination of small stimuli (~1.5cm, 0.5 degree) and large display fields. Under these conditions, they estimated that the threshold chromaticity difference is about 20~60 times the color discrimination threshold. Given that the Wyszecki-Fielder threshold is typically taken as 0.004 in the CIE uniform chromaticity systems, 60 times that threshold would be 0.24.

Identification

Color is often used denotatively to identify an object. Tasks using color for identification essentially involve color naming, in which observers can associate targets with specific color names in their mental processing. For example, colors may be used to identify different aircraft on ATC displays. In real life, identification of two stimuli is usually performed at separate spatial locations and times. Typically, an observer remembers the color by its name and then identifies the target by the color name. Color has been shown to be the most effective visual cue for identification tasks (Young & Nagy, 2003). On the other hand, several studies have demonstrated that labeling information with different levels of luminance did not help much in tasks involving quickly identifying targets, especially when memory was required (Sachtler & Zaidi, 1992).

There exist some controversial debates about the effects of color in identification tasks. Color and shapes are processed independently in the brain. When both codes are present, color is generally dealt with first, which makes sense in a search task but may not be the optimum strategy when the target location is known. Therefore, it was not a surprise that some studies suggested that color has little advantage in identification. For example, Luder and Barber (1984) asked subjects to identify the status of a known location on an aircraft cockpit display unit. Their results demonstrated that color-coding was not more helpful than achromatic coding. Also, Kahneman and Treisman (1984) found that attending to a red-colored letter only facilitated attention to redness but not to the meaning of the letter. Thus, they claimed that color helped search tasks but not identification.

Nevertheless, the majority of studies have demonstrated that color is the most effective attribute for labeling information in visual displays. In particular, for large displays with complex images, results in the literature are generally consistent about the superior role of color to achromatic cues (Christ, 1975). In a large display, a colored target can be found more quickly than achromatic targets, and the performance difference increases as the display size increases. When used to identify information such as aircraft shapes, geometric shapes, and alphanumeric signs, colors were significantly better (in terms of accuracy) than size, brightness, shape, and text. Christ further indicated that the identification of colors became increasingly superior to achromatic features as the difficulty of identifying achromatic features increased. Moreover, colors became increasingly more effective as recall was delayed.

Little research has been devoted to determining the threshold and saturation points of the effectiveness of color for identification. However, considerable data have been accumulated about color naming. Given that a task of using color for identification is essentially the task of color naming, we could determine the critical points based on color-naming studies. Berlin and Kay (1969) suggested that there might be only 11 categories of basic colors; each associated with a well-learned name and possibly unique physiological substrates. The 11 categories were: red, green, yellow, blue, purple, brown, orange, pink, and three achromatic names: black, white, and gray. Boynton and Olson (1990) confirmed this contention. They found that basic colors were maximally segregated in the color space. Boynton and Olson further showed that basic colors were superior to other colors in identification tasks because targets were identified more quickly and reliably. However, Smallman and Boynton (1990) found that the efficiency of color in identification is largely determined by color differences. They demonstrated that a set of non-basic colors with the same color differences as the basic colors had about the same effect in identifying targets, even though basic colors still had some superiority when the identification tasks involved complex scenes.

The threshold point for color in identification can be inferred from the color-naming threshold, which has been well examined by Boynton and his colleagues. Boynton, MacLaury, and Uchikawa (1989) reported that the color-naming threshold was about nine times the

color discrimination threshold. In a different approach, Poirson and Wandell (1993) found that the threshold for identifying a target by the color name is about seven times the color discrimination threshold. Poirson and Wandell asked subjects to detect a color target in a set of briefly presented objects. This kind of identification task was easier because subjects were asked only to identify one color at a time, while air traffic controllers often need to associate several colors with different types of information in ATC displays. Thus, the threshold determined by Boynton et al. (1989) is more appropriate to assess the effectiveness of color in ATC displays. We took nine times the discrimination threshold as the critical threshold point for identification tasks, which is $9 \times 0.004 = 0.036$. On the other hand, the differences between basic colors are at least 40 times the discrimination threshold; therefore, we took the color difference of 40x0.004 = 0.16 as the saturation point for Identification tasks.

Segmentation

When viewing a complex scene, the human visual system first organizes the scene into meaningful objects. To appreciate what and where particular objects are present, the visual input is organized by a filtering procedure that has been termed *segmentation* (Pinker, 1984). Segmentation becomes crucial when dealing with an automation system that is usually characterized by a cluttered display and varying task demands. Since color is processed separately from achromatic features by the visual system, it is one of the ways to segment a display into separate regions.

Segmentation is based on uniformity and consistency. An area composed of uniform elements can be segmented easily from its surround. Hence, in a real display, color is usually more effective than form cues for segmentation because form cues are used with explicit meaning. Nothdurft (1993) compared the effectiveness of visual cues that involved texture segmentation. He reported that, while color and luminance differences were both effective in producing regional segmentation and figure-ground organization, color information is dealt with first before achromatic cues. On the other hand, the experiment performed by Yamagishi and Melara (2001) indicated that luminance information was more effective than color to extract boundary representations, while chromaticity information is more effective in regional segmentation.

In the ideal situation, where the objects are homogeneous visual stimuli, the threshold color differences for segmentation are the same as the discrimination thresholds. However, completely homogeneous stimuli carry little information. That is a rare situation in ATC displays, which are typically composed of various text and symbols. Thus, we should review the literature in texture segmentation for the threshold points.

The luminance discrimination threshold has been well studied. The ratio between the threshold and the baseline luminance of an object is a constant for most of the luminance range produced by a display. The ratio is about 0.05 for uniform stimulus areas placed side-by-side. McIlhagga, Hine, Cole, and Snyder (1990) reported that the ratio for texture fields is about 0.15~0.2. Two texture regions with a luminance difference above the threshold ratio can be reliably segmented. Hence, we took 0.2 as the critical luminance threshold point for segmentation. As for color, the typical color discrimination threshold is about 0.004 for uniform stimuli placed side-by-side. The threshold increases as the stimulus areas become less uniform. Industries typically use three times the standard color discrimination threshold for texture discrimination. We thus took 3×0.004 as the threshold point of chromaticity difference for segmentation. There is little data about the saturation point for segmentation in the literature. However, it is reasonable to assume that the effectiveness of color in segmentation increases with chromaticity difference.

Text readability

ATC tasks involve considerable text reading because text comprises a relatively large part of the materials on displays. Text readability is defined as the property that permits an observer to read text easily on a screen irrespective of their meanings. In visual displays, readability is measured as the time required to find and read given text, or the number of words read per minute. Many experiments have demonstrated that text readability is predominately determined by the luminance contrast between the text and its background. Luminance contrast of text can be defined in several ways. Among those, Michelson's contrast definition is most widely used. It is defined as follows:

C=(Lt-Lb) / (Lt+Lb)

Where Lt is text luminance and Lb is background luminance. The contrast *C* varies between 0 and 1.

The effect of color in text reading is not as clear as that of luminance. Knoblauch, Arditi, and Szlyk (1991) examined the role of color in text reading. They found that, when luminance contrast is greater than 0.1, reading performance was unaffected by the presence of chromatic contrast over a range of character sizes varying 30-fold; only when luminance contrast was reduced to near the threshold for reading did chromatic contrast sustain reading. Ojanpaa and Näsänen (2003) measured the reading rate at different luminance contrasts while keeping the

color contrast constant. Interestingly, the results showed that reading rate decreased strongly when the luminance contrast approached zero. Thus moderate color contrast was not sufficient for effective visual search or reading when the luminance contrast was small. These findings may be because at high spatial frequencies, such as text, contrast sensitivity for pure color information is considerably lower than for luminance information.

Other studies seem to suggest a stronger role of color in reading. Pastor (1990) evaluated displayed colors by having subjects rank text readability. The results showed that color saturation had the most important influence on ratings. A similar experiment performed by Van Nes (1986) also demonstrated that white, yellow, cyan, and green yielded higher rating scores than magenta, blue, and red. In addition, Cowan and Ware (1987) reported that high brightness colors received high rankings for readability. However, all these results can be explained by the fact that the colors yielding great readability were the ones with high luminance.

Legge and his colleagues have performed a series of quantitative studies on text readability (Legge, Parish, Luebker, & Wurm, 1990). They measured reading speed as a function of luminance contrast, color contrast, or both. They found that reading speed decreased by approximately a factor of two when text contrast (Michelson contrast) decreased from 100% to 20%. This result implied that there was no saturation point in the effect of luminance contrast on reading. However, below 20% reading speed slowed much more rapidly and was significantly below the normal reading speed. Thus, a text contrast of 20% can be referred to as the threshold point for reading. This threshold choice is supported by other studies. For example, Scharff and Ahumada (2002) measured text readability as the time needed to search and read given text. The results indicated that text readability increased with contrast and deteriorated significantly for contrasts below 20~30%. In addition, Travis, Bowles, Seton, and Peppe (1990) suggested that luminance contrast should be about 50% for text reading on displays, to stay away from the threshold contrast for reading.

Redundant cues

When achromatic visual features are used in addition to colors to code information, those features are considered as redundant cues. Christ (1975) defined redundant cue as follows: "Target attributes were considered to be redundant if the target could be identified either in terms of colors or achromatic visual features." By this definition, the color and redundant cues of a target should be perfectly correlated. Target attributes were considered to be non-redundant if the targets could be identified or located only in terms of their color or achromatic features. If a task was to identify one attribute as the critical target feature and allowed one or more attributes to vary uncorrelatedly, that was also non-redundant.

Color and redundant cues may have different efficiencies in various color-related tasks. For example, a flashing signal is more effective than colors in drawing attention because the majority of the visual field is more sensitive to dynamic signals than to static ones. Among static visual features, while colors have been shown to be the most effective cue for attention and target search (Young & Nagy, 2003), a number of achromatic visual features, such as luminance, shape, and texture orientation, can also produce pop-out (Treisman & Souther, 1985). Another cue is the spatial location, provided that the information always appears at the same location, and one can easily remember it. Yantis and Jonides (1996) have demonstrated that sudden onset of a target at a known location captured attention.

Christ (1975) summarized the data in the literature about the effectiveness of colors relative to achromatic attributes. He calculated a difference score, which was the difference between performance with color in displays and without color in displays divided by the results obtained without colors. The maximum scores reported in the literature for *Identification* tasks were 202% for geometric shape, 176% for size, 62% for other shapes, 46% letters, and 19% for digits. The scores for *Attention* tasks were 53% for geometric shapes and 69% for other shapes. The positive values of these scores indicated that color was the most effective cue in both types of tasks. The effectiveness of achromatic cues relative to each other could also be inferred from the differences in the scores.

Algorithms to assess the effectiveness of color-coding and achromatic redundant cues for CDs

The goal of this section was to develop a computational method to assess how CDs use color-coded information relative to CNs. We approached the goal through the following steps:

1. Assess the effectiveness of color for CDs relative to CNs. This could be done by combining a dichromate simulation program and the experimental results of effectiveness of color reviewed in the previous section. While the effectiveness of color might vary continuously with color parameters in most situations, we classified the results of comparisons into three levels: "E" referred to situations where color was equal to or more effective for CDs than for CNs; "L" represented situations where color was less effective for CDs than for CNs; and "NE" meant that color was not effective for CDs. In addition, we used "NA" to denote the "not applicable" situation where color was not even effective for CNs. No comparison of color effects between CDs

and CNs was made for "NA" situations.

2. Assess the effectiveness of achromatic redundant cues. We also used a three-level scale, E, L, and NE, to classify the effects of color relative to achromatic cues. Once again, "NA" represented the situation where color was not effective for CDs.
3. The usefulness of color for CDs depended on both types of effectiveness. The overall usefulness was determined by a "winner-takes-all" rule, i.e., by the higher level of the two. For example, if the effect of color is "L" while the effect of redundant cues is "E," the overall effect is "E." It means that CDs, with the aid of redundant cues, could perform the color-related task equally well as did CNs.

We could use either the algorithm developed by Brettel et al. (1997) or Dougherty's *Vischeck* program to compute the perceived color for CDs. The two methods are equivalent for simple color stimuli. For complex scenes, the *Vischeck* program simulates color perception more accurately because it takes spatial interaction of color into consideration. Both methods allow simulations of deuteranopia, protanopia, and tritanopia. Since tritanopia is rare, we do not include this type in our analysis below. We analyzed the effects of color for deuteranopes and protanopes, respectively, and then combined the effects as the final assessment for CDs. The combination rule was opposite of "winner-takes-all," i.e., the final effectiveness of color for CDs was determined by the lower value of the effectiveness for deuteranopes and protanopes.

Attention

The effects of color in drawing attention depend on the visual conspicuity of the target, which, in turn, depends on the color and luminance differences between the target and distractors. Most visual displays have a dark background, so conspicuity of a target usually increases with the luminance of the target. According to our literature review, there is no saturation point in the relationship between conspicuity and the effectiveness of color in drawing attention. The threshold luminance difference for attention is $20 cd/cm^2$. The threshold chromaticity difference is 0.24 in the CIE uniform chromaticity systems.

We computed the effects of color on *Attention* using the following steps:

1. Convert the images from a color display into the images that would be perceived by CDs;
2. Determine chromaticity values (*Lxy*) for target, distractors, and background. This could be done either by colorimeter measurements or by formula transformation from *rgb* values on the display;
3. Compute color and luminance differences between the target and background, denoted as ΔCtb and ΔLtb; color difference is computed as $\Delta Ctb = ((\Delta u')^2 + (\Delta v')^2)^{1/2}$;
4. Compute color and luminance differences between the target and distractors, denoted as ΔCtd and ΔLtd;
5. Compute color and luminance differences between the target and distractors / background for CNs;
6. Compare the differences with the threshold and saturation points to determine the effects of color for CDs:

   If $\Delta Ctb < 0.24$ and $\Delta Ltb < 20$ for CNs, then the effect is "NA"
   If $\Delta Ctd < 0.24$ and $\Delta Ltd < 20$ for CNs, then the effect is "NA"
   If $\Delta Ctb < 0.24$ and $\Delta Ltb < 20$ for CDs, then the effect is "NE"
   If $\Delta Ctd < 0.24$ and $\Delta Ltd < 20$ for CDs, then the effect is "NE"
   Else,
   If both ΔLtb and ΔLtd for CDs are equal to or greater than those for CNs, then the effect is "E"
   If ΔCtb and ΔCtd for CDs are equal to or greater than those for CNs, then the effect is "E"
   If ΔLtb or ΔLtd is less for CDs than for CNs, then the effect is "L"
   If ΔCtb or ΔCtd is less for CDs than for CNs, then the effect is "L"

We applied the above procedure to ATC displays. While an ATC display may have many colors and luminance, it should have one or two default colors with which the majority of materials are displayed, and they are not considered as color-coding. In primary ATC displays such as Display System Replacement (DSR), the default colors are white, green, or yellow-green. The background color is typically black or dark blue. One problem with ATC displays is that controllers can adjust screen brightness to their own preferences, and sometimes they can adjust the luminance of different types of displayed messages individually. We mimicked these two situations by a) having the target and distractors all in the 100% luminance of the given color, mimicking that controllers adjust the overall brightness of the screen; and b) having the target in 100% luminance and distractors in 50% luminance, mimicking that controllers adjust the brightness of the default color (such as that of datablocks) but not the overall brightness.

We computed the effectiveness of some target colors for *Attention*. The computation was made for the ten colors that are frequently used to draw attention in ATC displays: red, green, yellow, blue, orange, brown, pink,

purple, cyan, and magenta. The background color was 20% gray. The distractor color was white, green, or yellow-green in 100% or 50% brightness. The results are shown in Table 1, with the rows specifying target color and the columns specifying distractor color. The comparison between the effects of color for CDs and for CNs are represented in the three scales stated earlier: "E" means equally effective for both CDs and CNs, "L" means "less effective" compared with CNs, and "NE" means "not effective" for CDs. The majority of data in Table 1 are "NE," suggesting that color is not an effective attention attribute for CDs.

Identification

The effects of color for *Identification* depends on the chromaticity differences between colors and how well colors can be named. Since luminance is not an effective cue for *Identification*, we only need to compute chromaticity differences between colors that are used to identify different categories of information and the differences between target colors and the background. The critical points of color difference are 0.036 for threshold and 0.16 for saturation. We computed the effectiveness of color for *Identification* by CDs using the following steps:

1. Convert the images from a color display into the images that would be perceived by CDs;
2. Determine chromaticity values for the background color and the colors that are used to identify information for CDs;
3. Determine chromaticity values for the background color and the colors that are used to identify information for CNs;
4. Compute the color difference ΔC for each pair of colors for CDs and color difference $\Delta C0$ for CNs.
5. Compare the color differences with critical points to determine the effects of color for CDs:

   If $\Delta C0 < 0.036$, then the effect is "NA"
   For the situations where $\Delta C\ 0>=0.08$,
   If $\Delta C <0.036$, then the effect is "NE"
   If $\Delta C >=0.16$, then the effect is "E"
   When $0.036 <= \Delta C <0.16$,
   if $\Delta C > = \Delta C0$, then the effect is "E"
   if $\Delta C < \Delta C0$, then the effect is "L"

We applied the above procedure to ATC displays to compute the effectiveness of color in *Identification* tasks for CDs. The background color was assumed to be at 20% gray. The computation was made for the same ten colors as those in Table 1. In addition, we added three typical default colors and one background color to the list: white, gray, yellow-green, and black. The results are shown in Table 2. A majority of the data in Table 2 are "L" and "NE," suggesting that many of the colors are either less effective or not effective in identification tasks for CDs.

Segmentation

The effects of color for *Segmentation* mainly depend on the color difference of the object and its surround. While the chromaticity information is processed first in visual segmentation, some achromatic cues such as luminance differences can also result in segmentation when no color difference is present. Since the effect of segmentation is largely determined by the uniformity

Table 1. Effect of color in *Attention* for CDs relative to CNs.

Distractor / Target	100% distractor luminance			50% distractor luminance		
	Green	White	Yellow-green	Green	White	Yellow-green
Red	NE	NE	NE	L	E	E
Green	NE	L	NE	NE	E	E
Yellow	L	L	NE	L	E	E
Blue	NE	NE	NE	NE	L	L
Purple	NE	NE	NE	L	L	L
Brown	NE	NE	NE	L	L	L
Orange	L	L	L	E	E	E
Pink	L	NE	L	L	L	L
Magenta	NE	L	NE	L	L	L
Cyan	L	L	L	E	E	E

Table 2: Effect of color in *Identification* for CDs relative to CNs.

	Red	Green	Yel	Blu	Pur	Bro	Oran	Pink	Cyan	Mag	Black	White	Gray	YG
Red	NA	NE	NE	L	L	NE	L	NE	L	L	L	L	L	NE
Green	NE	NA	NE	E	E	NE	L	NE	E	NA	E	E	E	NE
Yellow	NE	NE	NA	L	E	NE	E	NE	L	E	L	L	L	NE
Blue	L	E	L	NA	NE	L	L	E	E	L	E	E	E	E
Purple	L	E	E	NE	NA	L	L	E	NA	NE	E	E	E	E
Brown	NE	NE	NE	L	L	NA	E	NE	L	E	L	L	L	NE
Orange	L	L	E	L	L	E	NA	L	NE	L	NE	NE	NE	L
Pink	NE	NE	NE	E	E	NE	L	NA	L	NA	E	E	E	NE
Cyan	L	E	L	E	NA	L	NE	L	NA	E	NE	NE	NE	L
Magenta	L	NA	E	L	NE	E	L	NA	E	NA	NA	NA	NA	E

of an object or a local visual region, achromatic cues are not as effective as color unless the object or the area is completely uniform. According to our literature review, the threshold color difference for segmentation is about 0.012 and the threshold luminance difference is about 20% of the baseline luminance of the object to be segmented. The effects of segmentation increase with the differences between an object and the surround. Based on these results, we computed the effectiveness of color for *Segmentation* using the following steps:

1. Convert the images of a color display into the images as seen by CDs;
2. Determine the chromaticity values of the object and surround colors for CDs;
3. Determine the chromaticity values of the object and surround colors for CNs;
4. Compute the color difference ΔC between the object and surround, and the relative luminance difference ΔRL, defined as the luminance difference between the object and surround divided by the object luminance;
5. Compare the differences to critical points to determine the effects of color:

   If ΔC < 0.012 and ΔRL < 0.2 for CNs, the effect is "NA"

   Else,

   If ΔC < 0.012 and ΔRL < 0.2 for CDs, then the effect is "NE"

   If ΔC >= 0.012 for CDs and ΔC is equal or greater for CDs than for CNs, then the effect is "E"

   If ΔC >= 0.012 for CDs and ΔC is less for CDs than for CNs, then the effect is "L"

   If ΔC < 0.012 for CDs and ΔRL >=0.2 for CDs, the effect is "L"

We applied the above algorithm to ATC displays to compute the effects of color for *Segmentation* by CDs. The results are listed in Table 3, with rows for object color and columns for surround color. Notice that, except the identical object-surround colors (those along the diagonal line of the Table), all the other combination of colors are effective for segmentation by CDs and CNs. The comparisons between CDs and CNs are either "E" or "L," but not "NE," indicating that color is an effective cue in segmentation tasks even for CDs. Furthermore, some "less effective" color combinations for CDs do not necessarily mean less effective in real-life task performance. As long as an object, such as the menu bar of a display, can be segmented from its surround, observers can direct their eyes to that location, regardless of greater or less segmentation.

Text readability

Text readability is mainly determined by luminance contrast between the text and background. Readability increases with luminance contrast. When luminance contrast is near the threshold for reading, a color difference can sustain reading but is not as effective as the luminance factor. Moreover, there is no additive effect between color contrast and luminance contrast in readability. Therefore, we only considered the contribution of the luminance factor to reading. Based on the literature review, we took 20% Michelson contrast as the threshold point for reading. Hence, we computed the effects of color in text readability for CDs using the following steps:

1. Convert the images from a color display into the images that would be perceived by CDs;
2. Determine the chromaticity values of text and background colors for CDs;

Table 3: Effect of color in *Segmentation* for CDs relative to CNs.

	Red	Green	Yel	Blu	Pur	Bro	Oran	Pink	Cyan	Mag	Black	White	Gray	YG
Red	NA	L	L	L	L	L	L	L	L	L	L	L	L	L
Green	L	NA	L	E	E	L	L	L	E	E	E	E	E	L
Yellow	L	L	NA	L	E	L	E	L	L	E	L	L	L	L
Blue	L	E	L	NA	L	L	L	E	E	L	L	L	L	E
Purple	L	E	E	L	NA	L	L	E	E	L	E	E	E	E
Brown	L	L	L	L	L	NA	E	L	L	E	L	L	L	L
Orange	L	L	E	L	L	E	NA	L	L	L	L	L	L	L
Pink	L	L	L	E	E	L	L	NA	L	E	E	E	E	L
Cyan	L	E	L	E	E	L	L	L	NA	E	L	L	L	L
Magenta	L	E	E	L	L	E	L	E	E	NA	E	E	E	E
Black	L	L	E	L	E	L	L	E	L	E	NA	L	L	E
White	L	L	E	L	E	L	L	E	L	E	E	NA	E	E
Gray	L	L	L	L	E	L	L	E	L	E	E	L	NA	E
Yellow-green	L	L	L	E	E	L	L	L	L	E	E	E	E	NA

3. Determine the chromaticity values of text and background colors for CNs;
4. Compute Michelson contrast for CDs: $C=(Lt-Lb)/(Lt+Lb)$, where Lt is the text luminance and Lb is the background luminance;
5. Compute Michelson contrast $C0$ for CNs;
6. Compare the contrasts to critical points for text readability to determine the effects of color for reading:
   If $C0 < 0.2$, then the effect is "NA"
   Else
   If $C < 0.2$, then the effect is "NE"
   When $C >= 0.2$,
   If $C >= C0$, then the effect is "E"
   If $C < C0$, then the effect is "L"

We applied the above procedure to ATC displays. We calculated and compared the text readability of 14 colors by CDs and CNs. The results are shown in Table 4, with the columns for background color and rows for text color. When determining the background luminance, notice that even a background in its lowest *rgb* setting ($r=g=b=0$) still has some residual luminance due to illumination of visual stimuli on a computer screen and ambient light. An easy way to estimate the residual luminance is by simply treating a dark screen as a setting of 20% gray. For most computer monitors, the luminance produced by *rgb* values below 20% of the maximum *rgb* setting can hardly be discriminated by human eyes. With this assumption, the black color in Table 4 is actually specified with $r=g=b=50$. Notice that many combinations of text – background colors result in "NA" even for CNs. There are also many cases of "NE" for CDs. Therefore, colors should be chosen carefully when used to highlight a text because the highlighting color may result in low text readability.

Effect of redundant cues

One argument about the effects of using color in displays on the task performance of CDs is that they can use redundant achromatic cues to acquire color-coded information. Redundant cues in ATC displays include flashing, location, brightness/luminance, shape, size, and text. The literature review has shown that achromatic cues are not always as effective as colors. We next synthesize the results.

Redundant cues for attention:

- Flashing has been demonstrated to be the most effective cue in drawing attention. Thus, its effectiveness is greater or at least equal to color;
- A stimulus location by itself cannot draw attention; however, a sudden onset of a stimulus can draw attention to a known location. In this case, location can be equally effective to colors;
- High luminance / brightness is equal to or more effective than colors;
- Shapes can draw attention only if they are significantly different from distractors; however, they are far less effective than colors;
- Size and text are of limited use in drawing attention.

Redundant cues for identification:

- Flashing and luminance are not effective in identifying different categories of information because the visual system does not reliably register the levels of flashing or luminance in the mental processing;

Table 4: Effect of color in text readability for CDs relative to CNs.

	Red	Green	Yel	Blu	Pur	Bro	Oran	Pink	Cyan	Mag	Black	White	Gray	YG
Red	NA	E	E	NE	NE	E	E	NE	E	NA	NE	E	E	E
Green	E	NA	NA	E	E	L	NA	NA	NA	E	E	NE	NA	NA
Yellow	E	NA	NA	E	E	L	L	NA	NA	E	E	NA	E	L
Blue	NE	E	E	NA	NA	NA	E	NE	E	L	NA	E	E	E
Purple	NE	E	E	NA	NA	NA	E	NE	E	L	NA	E	E	E
Brown	E	L	L	NA	NA	NA	NE	L	L	L	NA	L	NE	NE
Orange	E	NA	L	E	E	NE	NA	NA	E	E	E	L	NA	NA
Pink	NE	NA	NA	NE	NE	L	NA	NA	NA	E	NE	E	NA	NA
Cyan	E	NA	NA	E	E	L	E	NA	NA	E	E	NA	NA	E
Magenta	NA	E	E	L	L	L	E	E	E	NA	L	E	E	E
Black	NE	E	E	NA	NA	NA	E	NE	E	L	NA	E	L	L
White	E	NE	NA	E	E	L	L	E	NA	E	E	NA	E	L
Gray	E	NA	E	E	E	NE	NA	NA	NA	E	L	E	NA	NA
Yellow-green	E	NA	L	E	E	NE	NA	NA	E	E	L	L	NA	NA

Table 5: Effect of achromatic redundant cues relative to colors.

	Flashing	Location	Luminance	Shape	Size	Text
Attention	E	L	E	NE	NE	NE
Identification	NA	E	NE	L	NE	L
Segmentation	NA	L	L	L	L	NE

- Location is effective only in situations where the types of information are fully correlated with locations;
- Size can be used to identify information only up to 2 or 3 categories (big, small, and maybe medium). Size is less effective than color or not effective at all when identification tasks are difficult;
- Shape and text are less effective than color for tasks involving complex scenes.

Redundant cues for segmentation:

- Color is superior to achromatic cues in segmenting complex visual scenes;
- Flashing is not an appropriate cue for information organization;
- Location is effective for segmentation, provided that different categories of information are spatially well-separated;
- Luminance is a less effective cue for segmentation than color;
- Shape and size may be used for organizing information because differences in spatial frequency and orientation of visual stimuli can result in figure-background segmentation; these cues are much less effective than color.
- Text is not effective in segmentation because of its heterogeneity.

Table 5 summarizes the above results. The three types of tasks, *Attention*, *Identification,* and *Segmentation* are listed in rows, and achromatic cues are listed in columns. The effectiveness of achromatic cues relative to colors is represented in three scales: "E" refers to the situation where the achromatic cue is of equal effectiveness to color, "L" means that the achromatic cue is less effective than colors, and "NE" means that the attribute is not effective for the given task. In addition, "NA" represents the situation where color is not effective. In this case, no comparison between color and achromatic attributes was made. Many elements in Table 5 are "L" and "NE," suggesting that, in many situations, the presence of redundant cues may not help CDs to perform color-related tasks as much as they do for CNs.

DISCUSSION AND CONCLUSIONS

This report synthesized previous visual studies about the effects of color on *Attention*, *Identification*, and *Segmentation* tasks, as well as text reading. Accumulative research has provided us with a profound understanding of color information processing. The purpose of this report was to apply those results to assess the potential effects of color vision deficiencies on ATC task performance. We first synthesized the data in the literature. Based on those results, we then developed algorithms to compute the effectiveness of color on the task performance by CDs. We also analyzed the effectiveness of the presence of achromatic redundant cues relative to color. Combining these, we are able to assess the overall impact on the performance by CDs in using color displays.

We provided a set of look-up tables and algorithms to assess the impact of color vision deficiencies for performance of each of the primary tasks: attention, identification, segmentation, and text reading The look-up tables are easy to use, but the results are available only for a limited set of colors. The look-up tables are based on some general assumptions about ATC displays. The effectiveness of color for CDs was simplified into three levels: Color was equally effective for CDs as it was for CNs, less effective relative to CNs, and non-effective. On the other hand, the algorithms allow more quantitative comparisons between CDs and CNs. One shortcoming is that both the algorithms and the look-up tables are based on Brettel's algorithm (1997) that simulates severe color vision deficiencies, in which one or two types of cones are completely absent from retinas. Many individuals have mild color vision deficiencies, in which the number of a certain type of cones is less than normal, or the cones are less sensitive than normal.

The algorithms in this report were developed to address the general concerns associated with the performance of color vision deficient controllers on the newer color displays that have been introduced in ATC facilities. However, they can be extended to evaluate other aspects of ATC displays. Without converting color images into what would be seen by CDs, we can use the algorithms to assess the effectiveness of color-coding for CNs. While it is desirable that color be used effectively for CNs, it is not always true for ATC display designs. The look-up tables contain many elements labeled as "NA," meaning that the specific combination of colors is not effective even for observers with normal vision. Therefore, such combinations should be avoided in ATC displays. For example, red-colored messages have been frequently used for emergency alerts. However, because red does not produce a high luminance, a red target often appears dimmer than other materials on a display. As the result, red-colored text is not very effective in drawing attention.

Finally, we need to point out that the algorithms and look-up tables are based on experimental data obtained in research labs. There are differences between situations in labs and operational facilities. For instance, subjects in research labs are assumed to fully attend to given tasks; their performance may be better than in an operational setting, where controllers are required to simultaneously perform several tasks, and they may not fully focus their attention on a single task. On the other hand, controllers may use color-coded information more efficiently than subjects in labs because controllers have been exposed to the same kind of visual stimuli on a daily basis for some time. Their experience and familiarity with color-coding could improve the efficiency of color use. In addition, the effects predicted by the algorithms may differ, depending on the extent of the color vision deficiency. We also made no effort to separate the use of color for the more critical safety-related tasks against those tasks that are less critical. Therefore, the results provided by this report should only be used for an initial assessment. Once we determine the situations in which color-coding may not be effective for CDs, high fidelity experiments will follow to examine the exact effects of color on CDs' task performances.

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APPENDIX A

A Transformation Between Color Systems

Colors in a computer display can be described by the tri-stimulus color system. This system specifies a color with three photometric quantities: R, G, and B. Given (r, g, b) as the 8-bit DAC values for each of the red, green, and blue channels of a monitor, the relationship between RGB values and DAC values is determined by the following equations:

$R=(r/255)^{2.2}$

$G=(g/255)^{2.2}$

$B=(b/255)^{2.2}$

The transformation between the RGB system and CIE chromaticity (Lxy) is determined by the following equations:

$X=40.9568*R + 35.5041*G + 17.9167*B;$

$Y=21.3389*R + 70.6743*G + 7.98680*B;$

$Z=1.86297*R + 11.4620*G + 91.2367*B;$

And,

$x=X/(X+Y+Z)$

$y=Y/(X+Y+Z)$

$L=Y$

Note that the parameters in these transformations vary from monitor to monitor. The parameter values used here are typical default values for CRT displays.

The CIE 1976 uniform chromaticity coordinates u´, v´ are given by

$u' = 4x / (-2x+12y+3)$

$v' = 9y / (-2x+12y+3)$